

Hydrogenation catalysts

The present invention relates to catalysts, which are useful for asymmetric
5 hydrogenation reactions.

Asymmetric hydrogenation is often an essential step in the synthesis of
enantiomerically pure products. Due to the increasing utilisation of pure enantiomers
as pharmaceuticals, catalytic hydrogenation reactions of this type have been widely
10 investigated during the last decade.

Both homogeneous and heterogeneous catalysts are suitable for asymmetric reactions.
WO 93/01199 describes chiral catalysts based on 1,2-bis(2,5-
dialkylphospholano)benzene, also known as "DUPHOS" ligands.

15 WO 01/64637 describes the use of homogeneous catalysts containing chiral ligands
such as DUPHOS for the asymmetric hydrogenation of prochiral alkenes. Those
catalysts provide relatively good selectivity and conversion rate, but they can not easily
be recovered from the reaction mixture.

WO 02/36261 describes metal-ligand complexes such as metal-DUPHOS immobilised
20 on mesoporous alumino silicates. These heterogeneous catalysts are more easy to
handle and to remove from the reaction mixture. However, these catalysts seem to
become deactivated relatively rapidly when used several times. Moreover, when used
for the hydrogenation of prochiral alkenes, relatively high amounts of catalyst in
relation to the prochiral alkene are needed in order to obtain good results, typically in
25 the range of 1:100-5000 (metal: substrate molar ratio).

The present invention overcomes these problems.

The invention relates to a catalyst comprising a chiral transition metal - (1,2-bis(2,5-
dialkylphospholano)benzene) complex immobilised on a zeolitic support having

- 30
- a molar ratio $\text{SiO}_2 / \text{Me}_2\text{O}_3$ of between 5 and 50, wherein Me designates an
element of valence 3 and
 - an external surface area, as developed by pores having a mean diameter higher
than 0.8 nm, of at least $90 \text{ m}^2 / \text{g}$.

BESTÄTIGUNGSKOPIE

Zeolites can be described as crystalline, (hydrated) metallosilicates with a framework structure. Their three-dimensional, polyanionic networks are constructed of SiO_4 and MeO_4 tetrahedra linked through oxygen atoms. Me designates an element of valence 3. The substitution of Si by an element of valence 3 generates a charge imbalance, necessitating the inclusion of a cation.

Zeolites can be represented by the chemical formula $M_{x/n}(\text{MeO}_2)_x(\text{SiO}_2)_y(\text{H}_2\text{O})_z$ where M is the charge compensating cation (such as sodium, potassium, magnesium and calcium), n is the cation valence and z represents the moles of water contained in the zeolitic voids. In general, z is between 0 and $2(x+y)$.

The preferred zeolites are the aluminosilicates, where Me is aluminium. Many zeolites occur naturally as minerals, but there are also synthetic zeolites, which have the same properties except that in some cases Al and Si have been replaced wholly or in part by other elements such as Ga, Fe, B, Ge or Ti.

Prior art techniques have resulted in the formation of a great variety of synthetic zeolites. These zeolites are designated by a letter, acronym or other convenient symbols, as illustrated by zeolite A, X, Y, L, ZSM-5 and BETA.

Both natural and synthetic zeolites can be used as support in the catalyst according to the present invention.

The zeolites can be used as powder. They can also be transformed via existing technologies into granules, extrudates or pellets. The formed samples usually contain between 0 and 60% binder like silica gel, alumina or clay.

The zeolitic support used in the present invention is preferably chosen between BETA and US-Y topology zeolites, more preferably between BETA zeolites.

BETA zeolites consist of an intergrowth of two distinct structures termed polymorphs A and B. The polymorphs grow as two-dimensional sheets and the sheets randomly alternate between the two. Both polymorphs have a three dimensional network of 12-ring pores. The intergrowth of the polymorphs does not significantly affect the pores in two of the dimensions, but in the direction of the faulting, the pore becomes tortuous, but not blocked. Recently, a pure polymorph C denoted ITQ-17 resulting from the intergrowth of zeolite BETA has been synthesized (A. Corma et al. Chem. Comm. (2001) page 1487 and WO 02/30819).

The US-Y zeolites useable for the catalyst according to the invention are generally US-Y zeolites which are dealuminated via steaming and acid leaching procedures, such as described in DE 199 13 395.

- 5 The zeolites used as supports in the catalysts of the present invention preferably have a $\text{SiO}_2/\text{Me}_2\text{O}_3$ molar ratio of at most 40 and most preferably of at most 30. The $\text{SiO}_2/\text{Me}_2\text{O}_3$ molar ratio is preferably of at least 6.

10 In the present invention, the external surface area (S_{ext}) is defined as the surface developed by pores having a mean diameter superior to 0,8 nm (non ultra-micropore volume). S_{ext} is obtained from the treatment of nitrogen adsorption isotherms recorded at 77K according to the procedure described in M.J. Remy, G. Poncelet. *J Phys Chem* **99** 773-779, (1995). Particularly suitable zeolitic supports are those having a S_{ext} of at least 200 m^2/g .

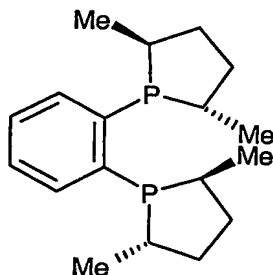
15 Particularly suitable zeolitic supports have an ultra-micropore volume of at least 0.08 cm^3/g .

The ultra-micropore volume V_{μ} is defined herein as the volume developed by pores with diameter smaller than 0.8 nm and can be measured according to the procedure
20 described in M.J. Remy, G. Poncelet. *J Phys Chem* **99** 773-779, (1995).

In the catalyst according to the invention, the transition metal is usually selected from rhodium (Rh), ruthenium (Ru), and iridium (Ir). It is preferably Rh or Ru and more preferably Rh.

25 The alkyl substituent in the 1,2-bis(2,5-dialkylphospholano)benzene (DUPHOS) comprises in general from 1 to 8 carbon atoms and is preferably methyl, ethyl or isopropyl. Most preferred is 1,2-bis(2,5-dimethylphospholano)benzene (Me-DUPHOS). The structure of (S,S)-Me-DUPHOS is shown below:

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The DUPHOS ligand may be associated to a counterion and/or an olefin.

The counterion is usually selected from halides, BPh₄(-), ClO₄(-), BF₄(-), PF₆(-), PCl₆(-), OAc(-), triflate, mesylate or tosylate. The preferred counterion is BF₄(-).

The olefin is usually selected from ethylene, 1,3-butadiene, benzene, cyclohexadiene, norbornadiene and cycloocta-1,5-diene (COD). Preferred is COD.

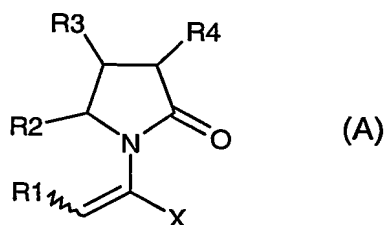
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The catalysts according to the invention may be prepared by common procedures known to the one skilled in the art, such as described in WO 02/36261. They may be obtained by impregnation of the zeolitic support with a solution of the transition metal-DUPHOS complex. Generally about 1 to 250 μ mol DUPHOS, preferably 5 to 10 μ mol, is used per g of zeolite.

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The catalyst of the present invention is useful for the hydrogenation of unsaturated substrates. The invention catalyst is particularly useful for the production of substantially enantiomerically pure products by hydrogenation of prochiral substrates such as alkenes, ketones, imines and ketimines containing double bonds and in particular for the hydrogenation of functionalised olefines. The solid catalyst is particularly useful for the hydrogenation of compounds of general formula (A) in the form of a Z or an E isomer, such as described in WO 01/64637:

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wherein X is -CONR⁵R⁶, -COOR⁷, -COR⁸ or -CN;

R¹ is hydrogen, alkyl, aryl, heterocycloalkyl, heteroaryl, halogen, nitro, cyano, acyl, ester, amido or carboxy,

R², R³, R⁴ are the same or different and each is, independently, hydrogen or halogen, hydroxy, amino, nitro, cyano, acyl, acyloxy, sulfonyl, sulfinyl, alkylamino, carboxy, ester, ether, amido, sulfonic acid, sulfonamide, alkylthio, arylthio, alkyl, alkoxy, oxyester, oxyamido, aryl, arylamino, aryloxy, heterocycloalkyl, heteroaryl, alkenyl;

R⁵ and R⁶ are the same or different and each is, independently, hydrogen, hydroxy, alkyl, aryl, heterocycloalkyl, heteroaryl, alkoxy, aryloxy; R⁷ is hydrogen, alkyl, aryl, heterocycloalkyl or heteroacyl; and

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R⁸ is hydrogen, hydroxy, thiol, halogen, alkyl, aryl, heterocycloalkyl, heteroaryl, alkylthio, arylthio.

The term "alkyl" as used herein, includes saturated monovalent hydrocarbon radicals having straight, branched or cyclic moieties or combinations thereof and contains 1-20 carbon atoms, preferably 1-5 carbon atoms, optionally substituted by 1 to 5 substituents independently selected from the group consisting of halogen, hydroxy, thiol, amino, nitro, cyano, acyl, acyloxy, sulfonyl, sulfinyl, alkylamino, carboxy, ester, ether, amido, sulfonic acid, sulfonamide, alkylthio, arylthio, oxyester, oxyamido, heterocycloalkyl, heteroaryl, (C1-C5)alkoxy, (C6-C10)aryloxy, (C6-C10)aryl.

The term "alkenyl" as used herein, is defined as including branched, unbranched and cyclic unsaturated hydrocarbon radicals having at least one double bond, optionally substituted such as described for alkyl radicals here above.

The term "heterocycloalkyl", as used herein, represents a cyclic alkyl, having at least one O, S and/or N atom interrupting the carbocyclic ring structure such as tetrahydrofuranyl, tetrahydropyranyl, piperidinyl, piperazinyl, morpholino and pyrrolidinyl groups or the same substituted by at least a group selected from halogen, hydroxy, thiol, amino, nitro, cyano.

The term "alkoxy", as used herein includes -O-alkyl groups wherein "alkyl" is defined above.

The term "alkylthio" as used herein, includes -S-alkyl groups wherein "alkyl" is defined above.

The term "alkylamino" as used herein, includes -NHalkyl or -N(alkyl)₂ groups wherein "alkyl" is defined above.

The term "aryl" as used herein, includes an organic radical derived from an aromatic hydrocarbon by removal of one hydrogen, such as phenyl or naphthyl, optionally substituted by 1 to 5 substituents independently selected from the group halogen, hydroxy, thiol, amino, nitro, cyano, acyl, acyloxy, sulfonyl, sulfinyl, alkylamino, carboxy, ester, ether, amido, sulfonic acid, sulfonamide, alkylthio, oxyester, oxyamido, aryl, (C1-C6)alkoxy, (C6-C10)aryloxy and (C1-C6)alkyl. The aryl radical generally consists of 1-3 rings, preferably one ring, and contains in general 3-30 carbon atoms, preferably 6-10 carbon atoms.

The term "arylamino" as used herein, includes -NHaryl or -N(aryl)₂ groups wherein "aryl" is defined above.

The term "aryloxy", as used herein, includes -O-aryl groups wherein "aryl" is defined as above.

The term "arylthio", as used herein, includes -S-aryl groups wherein "aryl" is defined as above.

The term "heteroaryl", as used herein, unless otherwise indicated, represents an "aryl" as defined above, having at least one O, S and/or N interrupting the carbocyclic ring structure, such as pyridyl, furyl, pyrrolyl, thienyl, isothiazolyl, imidazolyl, benzimidazolyl, tetrazolyl, pyrazinyl, pyrimidyl, quinolyl, isoquinolyl,

isobenzofuryl, benzothienyl, pyrazolyl, indolyl, isoindolyl, purinyl, carbazolyl, isoxazolyl, thiazolyl, oxazolyl, benzthiazolyl, or benzoxazolyl, optionally substituted by 1 to 5 substituents independently selected from the group consisting of hydroxy, halogen, thiol, amino, nitro, cyano, acyl, acyloxy, sulfonyl, sulfinyl, alkylamino, carboxy, ester, ether, amido, sulfonic acid, sulfonamide, alkylsulfonyl, alkoxycarbonyl, oxyester, oxyamido, alkoxycarbonyl, (C1-C5)alkoxy, and (C1-C5)alkyl.

The term "arylalkyl" as used herein represents a group of the formula aryl-(C1-C4 alkyl)-.

The term "acyl" as used herein, represents a group of formula alkyl-CO-, aryl-CO-, heteroaryl-CO- or arylalkyl -CO-, wherein the various hydrocarbon radicals are as defined in this section.

The term "acyloxy" as used herein, represents a group of formula alkyl-CO-O-, aryl-CO-O-, heteroaryl-CO-O- or arylalkyl-CO-O-, wherein the various hydrocarbon radicals are as defined in this section.

The term "sulfonyl" represents a group of the formula -SO₂-alkyl or -SO₂-aryl wherein "alkyl" and "aryl" are defined above.

The term "sulfinyl" represents a group of the formula -SO-alkyl or -SO-aryl wherein "alkyl" and "aryl" are defined above.

The term "sulfonamide" represents a group of formula -SO₂NH₂.

The term "ester" means a group of formula -COO-alkyl, or -COO-aryl wherein "alkyl" and "aryl" are defined above.

The term "oxyester" means a group of formula -O-COO-alkyl, or -O-COO-aryl wherein "alkyl" and "aryl" are defined above.

The term "ether" means a group of formula alkyl-O-alkyl or alkyl-O-aryl or aryl-O-aryl wherein "alkyl" and "aryl" are defined above.

The term "amido" means a group of formula -CONRR' wherein R and R' are independently selected from hydrogen, "alkyl" or "aryl".

The term "oxyamido" means a group of formula -O-CONRR' wherein R and R' are independently selected from hydrogen, "alkyl" or "aryl".

The catalyst is particularly suitable for the hydrogenation of substrates of formula (A) wherein R¹ is alkyl, R² and R⁴ are hydrogen, R³ is H, optionally halogenated alkyl or alkenyl and X is -CONH₂, -COOMe, -COOEt or -COOH and more particularly for the hydrogenation of methyl or ethyl(Z,E)-2-(2-oxotetrahydro-1H-1-pyrrolyl)-2-butenolate.

The invention therefore further relates to a process for the hydrogenation of unsaturated substrates such as described above wherein a catalyst according to the invention is used.

The temperature at which the process is conducted is generally comprised between 0 and 65°C, preferably between 15 and 30°C. The reaction is usually performed under hydrogen pressure in the range of 1 to 50 bar and preferably at 2 to 6 bar. In general, the amount of catalyst used in the process according to the invention is such that the
5 substrate: catalyst (transition metal) molar ratios are in the range of 20 to 50000:1. The substrate: catalyst ratio is preferably superior to 1000, most preferably superior to 5000.

Usually the hydrogenation reactions with the catalyst according to the present invention are performed in the presence of a suitable solvent. Preferred solvents are
10 selected from ethers, alcohols or mixtures thereof. More preferably the solvent is a mixture of ether and alcohol, particularly in a volume ratio 2:1. The most preferred solvent is diisopropyl ether and its mixture with methanol.

The use of ethers or mixtures of ethers with alcohols permits to have a particularly low degree of metal leaching.

15 The process according to the invention permits to obtain a high conversion, usually superior to 95 % and a high conversion rate. Surprisingly it has been found that the conversion is as rapid or can even be more rapid than with a homogeneous catalyst. The process according to the invention permits to obtain a high selectivity. The
20 catalyst according to the invention presents a high activity, so that very high substrate:catalyst ratios can be used. The catalyst presents a high activity at substrate:catalyst ratios higher than 5000, even higher than 10000 or 15000. Hence, the contamination of the final products with catalyst residues, especially with the transition-metal, is low. This also reduces the cost of the final product. Moreover the
25 catalyst according to the invention permits an easy recovery and reuse, which is ecologically and economically very advantageous.

The invention is further illustrated by the following examples. The results are summarised in Table 1 and Table 2.

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Example 1: Asymmetric hydrogenation of Methyl(Z,E)-2-(2-oxotetrahydro-1H-1-pyrrolyl)-2-butenate with $[\text{Rh}-(\text{S,S-MeDUPHOS})(\text{COD})\text{BF}_4^-]$ immobilised on BETA zeolite.

35 In a nitrogen atmosphere, 0.0129 g $[\text{Rh}-(\text{S,S-MeDUPHOS})(\text{COD})\text{BF}_4^-]$ was dissolved in degassed 6 ml methanol. The yellow solution was added to 3 g of an acid zeolite BETA provided by Uetikon in extrudate form (sample PB/65H). The impregnated solid was dried for 1 hour under vacuum.

Dry yellowish extrudates were obtained and stored in a nitrogen atmosphere.

A mixture of Z and E-isomers of Methyl-2-(2 oxotetrahydro-1H-1pyrrolyl)-2-butenolate (9.98 g) and 26.51 g of methanol were weighted into a 200 ml flask. The reaction mixture was degassed (3 × vacuum/nitrogen). The flask and a 50 ml AutoclaveFrance reactor were placed in a plastic glove box which was then purged by five vacuum/nitrogen cycles. The reactor was filled with 33.14 g of the degassed mixture and 1.1153 g of the dried catalyst. The substrate:catalyst molar ratio was 6795. The reactor was then pressurised with hydrogen to an initial pressure of 4.8 bar and then released to a pressure of 1 bar. This operation was repeated three times. Finally the reaction mixture was left to stir at room temperature at a constant hydrogen pressure of 4.8 bar.

Reaction samples were collected after 2 and 14 hours.

The products were analysed by chiral gas chromatography (using a HP 6890 equipped with a FI detector and a Chirasil-DexCB fused silica column) and atomic absorption spectroscopy (at 343.5 nm with a Varion Techtron AA6).

The conversion, turn-over frequency (TOF) and enantiomeric excess (% ee) are shown in Table 1.

The conversion is defined as [number of moles substrate converted/initial number of moles substrate in the reaction mixture]×100.

The TOF is defined as (number of moles substrate converted/number of moles DUPHOS)/time.

The enantiomeric excess is defined by the relative excess of one enantiomer to the other (%ee of S = $([S]-[R])/([R]+[S])\times 100$), in which [R] and [S] stand for the concentrations of both enantiomers in the reaction mixture).

Example 2:

Example 1 was reproduced except that diisopropylether was used as solvent. The reaction conditions and results are shown in Table 1.

Example 3:

Example 1 was reproduced except that a mixture of methanol and diisopropylether in a volume ratio 1:2 was used as solvent. The reaction conditions and results are shown in Table 1.

Example 4:

Example 1 was reproduced except that a mixture of methanol and diethylether in a volume ratio 1:2 was used as solvent. The results are shown in Table 1.

Comparative example 5R:

Example 1 was reproduced except that non-supported Rh-(S,S-MeDUPHOS)(COD)BF₄· was used as catalyst. The results are shown in Table 1.

Comparative example 6R:

- 5 Example 1 was reproduced except that the catalyst was supported on mesoporous alumino silicate Al-MCM-41 synthesized according to the procedure of Yu *et al.* (J.Yu, J.L. Shi, L.Z. Wang, M.L. Ruan, D.S. Yan, *Ceramics International* **26:(4)** 359-362 (2000)). The results are shown in Table 1.

10 Example 7:

Example 1 was reproduced except that the catalyst was supported on a US-Y zeolite (CBV 720) from Zeolyst. The properties of the zeolite and the results are shown in Table 1.

15 Comparative example 8R:

Example 1 was reproduced except that the catalyst was supported on a US-Y zeolite from Zeolyst (CBV 760). This zeolitic support had a SiO₂/Al₂O₃ ratio outside the scope of the invention. The properties of the zeolite and the results are shown in Table 1.

20 Comparative example 9R:

Example 1 was reproduced except that the catalyst was supported on a US-Y zeolite from Zeolyst (CBV 600) having an external surface area outside the scope of the invention. The properties of the zeolite and the results are shown in Table 1.

25 Example 10:

Example 1 was reproduced except that the catalyst was supported on a ZSM-5 zeolite. The properties of the zeolite and the results are shown in Table 1.

Table 1:

Ex n°	Support	SiO ₂ /Al ₂ O ₃ (1)	Sext (m ² /g) (2)	V _μ (ml/g) (3)	Solvent	S/C (%)	Time (h)	Conv. (%)	TOF (h ⁻¹)	ee (%)
1	Zeolite BETA	19.8	226	0.19	MeOH	6795	2.25	6.3	191.3	93.1
2	Zeolite BETA	19.8	226	0.19	DIPE	5556	20	98.1	283.6	99.2
3	Zeolite BETA	19.8	226	0.19	MeOH/DIPE	5882	15	100.0	376.3	99.2
4	Zeolite BETA	19.8	226	0.19	MeOH/Et ₂ O	6250	22	99.6	283.9	98.2
5R	-	-	-	-	MeOH	5882	48	98.1	119.1	96.2
6R	Al-MCM-41	20	610	-	MeOH	7143	19	12.5	47.1	95.8
7	Zeolite US-Y	26.0	103	0.27	MeOH	6250	18	68.7	242.7	97.1
8R	Zeolite US-Y	60.0	143	0.25	MeOH	5263	112	88.0	40.5	95.4

9R	Zeolite US-Y	5.6	51	0.24	MeOH	7143	139	95.7	50.4	94.0
10	Zeolite ZSM-5	50	112	0.14	MeOH	5882	17	49.7	171.0	96.4
							48	97.2	118.5	96.7

((1), (2) and (3): values corresponding to the pure zeolite).

Table 1 shows that the catalyst according to the invention permits to obtain a higher conversion rate in comparison with DUPHOS supported on supports having properties outside of the scope of this invention.

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Example 11:

Example 1 was reproduced except that dimethyl itaconate was used as substrate and a zeolite BETA supplied from Zeolyst (in powder form) was used.

10 The reaction conditions and results are shown in Table 2.

Example 12:

Example 11 was reproduced except that diisopropylether was used as solvent. The reaction conditions and results are shown in Table 2.

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Comparative example 13R:

Example 12 was reproduced except that a catalyst supported on a mesoporous alumino silicate Al-MCM-41 support having the properties described in Table 2 was used instead of the invention catalyst. The results are shown in Table 2.

Table 2:

Ex n°	Support	SiO ₂ /Al ₂ O ₃	Sext (m ² /g)	V _μ (ml/g)	Solvent	S/C (%)	Time (h)	Conversion (%)	TOF (h ⁻¹)	ee (%)
11	Zeolite BETA	26	192	0.19	MeOH	3984	1.0 2.1	74.7 99.0	2974 1894	97.6 97.4
12	Zeolite BETA	26	192	0.19	DIPE	17152	1.3 17.3	15.0 83.1	1932.4 821.9	100.0 98.1
13R	Al-MCM-41	20	610	-	DIPE	18517	1.3 18.7	0.7 4.7	96.2 46.8	100.0 91.3

Comparison of example 12 with comparative example 13R shows that the catalyst according to the invention permits to obtain high conversion rates, even at substrate:catalyst ratios exceeding 15 000.